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Nutrient Mobility and Availability with Selected Irrigation and Drainage Systems for Vegetable Crops on Sandy Soils

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1. Introduction

A wide variety of vegetable crops is produced on varying types of soils including sandy soils where the production can be maximized as long as proper fertilization, irrigation and drainage systems are implemented. However, most sandy soils have low water- and nutrient-holding capacities, hence appropriate irrigation scheduling is critical for proper plant health as well as for minimizing water requirement. Healthy crops are better able to withstand pest and disease pressures, as well as produce a high quality commercial product. Irrigation management should be geared towards maintaining optimum moisture and nutrient concentrations within the plant root zone. If this goal is achieved, crops will take up their maximum amounts of water and nutrients with minimum wastage. Equally important, excessive irrigation will reduce water use efficiency, as well as require more water and contribute to potentially negative environmental impacts.

It is crucial to recognize how nutrients move and transform in soils after the application for improved application efficiencies and reduced environmental losses. However, different irrigation and drainage systems practiced on sandy soils for vegetable production can complicate the dynamics of mobility and availability of nutrients and water. Yet, the number of researches on this matter has not been as many as needed. Therefore, this review attempts to summarize characteristics of sandy soils for vegetable production (Section 2), clarify pros and cons of different irrigation and drainage systems practiced on sandy soils (Section 3), and elucidate the nutrient mobility and availability for vegetable production under different irrigation systems specifically on sandy soils (Section 4), in which the soil environment can greatly differ from other soil types in terms of nutrient dynamics in soil.

2. Characteristics of sandy soils for vegetable production

2.1 Types and physiochemical properties of sandy soils

Soils on which crops are grown greatly influence how irrigation water, nutrients, and other agrichemicals should be managed to maximize the production while minimizing resource use and effects on the environment. Soil properties that influence soil water management

include soil texture, hydraulic conductivity, water-holding capacity, and natural drainage, which also affect soil nutrient management that differs depending on soil organic matter (OM) content, pH, cation exchange capacity (CEC), and coatings on sand grains.

Soil texture is the relative proportion of sand, silt, and clay in a mineral soil. Texture influences how much water a soil can hold against drainage by gravity and how quickly water drains away if it has an outlet. Sandy soils contain 80% or more sand in the root zone (Shirazi and Boersma, 1982). The high sand contents make irrigation water management extremely difficult because sands are dominated by large pores that have little capacity to hold water through capillarity (Kern, 1992). Therefore, if too much water is applied to the sandy soil, the excess is lost below the root zone and can induce nutrient leaching.

Soil OM includes anything that was once alive, from freshly deposited plant residues to highly decomposed humus. In their native state, sandy soils may contain as much as 5% OM under grass vegetation, and somewhat less under forest cover (Six et al., 1998). Cultivated soils usually contain less OM than native soils, typically less than 3%, due to decreased plant diversity and the use of herbicides or plastic mulches that reduce weed growth. Under well-drained conditions, soil OM is rapidly lost as carbon dioxide by oxidation in warm and humid climates, and is not replaced in large quantities by crop production because relatively low area is covered by plant materials at any given time. In sandy soils, OM is an extremely valuable component because it provides both water and nutrient-holding capacities, and its decomposition provides recycled nutrients to plants (Khaleel et al., 1981).

Soil water-holding capacity is provided by the smaller pores that exist between and within the smallest fraction of soil and OM particles (Khaleel et al., 1981). Therefore, the water-holding capacity is directly related to amounts of silt, clay, and OM present. Since sandy soils contain only minimal amounts of these components, their water-holding capacity is rarely greater than 2.5 cm per 30 cm of soil depth, and are often less than 1.9 cm per 30 cm.

2.2 Characteristics of subsurface layers

Argillic and spodic layers can be found underneath many surface sandy soils, and have considerably different physicochemical properties from the surface soils. The argillic layer is created by the deposition of clay particles and is usually mottled gray in color and sandy or sandy loam in texture. This horizon can be either acidic or alkaline with high clay content. The spodic layer is composed of OM that is leached down the profile by both physical and chemical means and deposited in the lower part of the soil profile. This distinct brown or black layer is often high in OM, aluminum, and iron, usually with a low pH, and almost always sandy in texture. Both argillic and spodic layers impede vertical water percolation and causes water to accumulate above these horizons because their permeability is low. This water accumulation is referred to as a perched water table, and is beneficial for maintaining a constant water table for subsurface irrigation for vegetable production (Muchovej et al., 2005). In addition, the water-holding capacity and CEC are typically higher in these subsurface layers than in the surface soils (Obreza & Collins, 2002).

The nutrient and irrigation managements can be different and may be complicated when these layers are excavated and mixed in as a result of the bedding process. The subsurface layers can be found relatively deep in some Alfisols and Spodosols in USA such as Holopaw (70 to 162 cm depth), Pineda (95 to 130 cm), Immokalee (90 to 137 cm), and Oldsmar series (95 to 125 cm), hence remain undisturbed following the bedding process. Other sandy soils

such as Riviera (57 to 135 cm), Winder (30 to 122 cm), Pomona (52 to 65 cm), and Wabasso series (62 to 85 cm) have relatively shallow argillic or spodic layers that can be excavated during the bedding process (Obreza & Collins, 2002; Gilbert et al., 2008). As a result, these subsurface materials are sometimes mixed into the root zone affecting physicochemical properties of the surface sandy soils (Obreza & Collins, 2002).

3. Irrigation and drainage systems on sandy soils

Irrigation can be defined as the artificial application of water to the soil for assisting in growing crops and is considered one of the most important cultivation practices in dry or limited rainfall areas and during periods with no or little rainfall. An approach to conserving water is to maximize the irrigation efficiency and to minimize water loss. Irrigation efficiency is a measure of the effectiveness of an irrigation system in delivering water to a crop and/or the effectiveness of irrigation in increasing crop yields. Good irrigation practices imply good irrigation efficiency and can be achieved by maintaining a good irrigation water application uniformity and improve water uptake efficiency of the irrigation water. Uniformity can be defined as the ratio of the volume of water used or available for use in crop production to the volume pumped or delivered for use. Crop uptake efficiency may be expressed as the ratio of increase in yield over non-irrigated production to the volume of irrigation water used. Irrigation efficiencies thus provide a basis for the comparison of irrigation systems from the standpoint of water beneficially used and from the standpoint of yield per unit of water used (Haman et al., 2005). Irrigation system efficiency depends primarily on design, installation and maintenance, and management. Thus, a properly designed and maintained system can be inefficient if mismanaged just as a well-designed system can be inefficient if managed effectively with poor maintenance. Irrigation management of vegetable crops includes: 1) combination of target irrigation volume, 2) measure of soil moisture to adjust this volume based on crop age and weather conditions, 3) knowledge of how much the root zone can hold, and 4) assessment of how rainfall contributes to replenishing soil moisture. (Hochmuth, 2007).

Concerns about the environmental impact of water and fertilizer uses by agriculture have dramatically increased in the past few decades. Crop production is linked to leaf photosynthesis and canopy size, and water stress drastically reduces both components (Kramer & Boyer, 1995). Adequate water supply is, therefore, critical in maximizing crop production, nutrient use efficiency (NUE), and quality of most horticultural crops. Efficient water use may promote an increase in fertilizer retention in the effective root zone, maximizing crop production and minimizing the potential of groundwater degradation (e.g., nitrate-nitrogen (NO_3^- -N) leaching) (Scholberg et al., 2002). A simple goal of the ideal irrigation scheduling would be to increase crop production with the least amount of water, therefore minimizing water loss by deep percolation, runoff or evaporation. However, no irrigation system has the capability of completely avoiding water losses, although several irrigation methods and techniques can be adopted to minimize losses and increase the water use efficiency by crops.

One of the most important irrigation management factors is irrigation uniformity, which is how evenly water is distributed across the field. Non-uniform distribution of irrigation water may create over- and/or under-irrigated areas which can lead to yield reduction due to excessive nutrient leaching or plant water stress. For a sprinkler irrigation system, the

uniformity of application can be evaluated by placing containers in a geometric configuration and measuring the amount of water caught in each container. Dukes et al. (2006) utilized this type of testing to show the effect of pressure and wind speed on operating performance of two types of center pivot sprinkler system nozzle packages. Furthermore, Dukes and Perry (2006) showed that uniformity of a variable rate control system was not different from a traditional control system on two typical center pivot/linear move irrigation systems used in the southeast USA. However, the problem with sprinkler systems is that the water application pattern is susceptible to distortion by the wind. While wind speed and direction are not controlled variables, their effect on irrigation uniformity is significant, so that sprinkler system design must be done with anticipated wind conditions. Drip irrigation systems are very efficient in terms of water distribution and reduction of water losses. The uniformity is directly related to the pressure variation within the entire system and the variability of the emissions of each individual emitter. Several factors contribute to reduce the uniformity of water application such as excessive length of laterals, excessive pressure losses due to changes in elevation along the laterals, emitter clogging, and soil characteristics. Limited lateral water mobility in sandy soils under drip irrigation drastically affects root distribution (Zotarelli et al., 2009), and nutrient interception in the sides of the raised bed. This could be a problem for double row crops like peppers and squash when a single drip tape is placed in center of the bed.

Non-uniform distribution of water in the bed may also compromise the acquisition of nutrients by the root system. Since NO_3^- -N is a highly mobile, non-adsorbing ion, low rooting densities may not be sufficient for NO_3^- -N acquisition, and a larger fraction of the N applied through fertigation can escape below the root zone. The basis for this lies in previous field observations which demonstrated that the displacement of irrigation water and nutrients is primarily vertical and confined to a 30–38 cm wide zone, due to the extremely high hydraulic conductivity of sandy soils (Zotarelli et al., unpublished data). The use of appropriate irrigation scheduling facilitates more frequent applications of small volumes of water and improves matching of water supply and crop water demand which is critical to reduce potential crop water stress and leaching losses in sandy soils (Zotarelli et al., 2008a, 2008b, 2009). Since applying frequent small volume irrigation with conventional systems tends to be labor-intensive and/or technically difficult to employ, sensor-based irrigation systems may facilitate the successful employment of low volume-high frequency irrigation systems in commercial vegetable systems. In addition, reduction in emitter spacing and also the use of double drip tapes placed closer to the crop rows may improve the uniformity of water and nutrient distribution along the beds, while reducing the amount of water required. However, there is a lack of information about the effectiveness of this system for double row crops.

3.1 Irrigation types and performance characteristics

Irrigated acreage world-wide spans a range of irrigation delivery systems depending on the type of crop and cultural conditions. Irrigation can be grouped into the following general categories: low volume (also known as microirrigation, trickle irrigation, or drip irrigation), sprinkler, surface (also known as gravity or flood irrigation), and seepage (also known as subsurface irrigation or water table control). These irrigation systems vary by application efficiency with surface and seepage being less efficient than microirrigation (Table 1).

Irrigation system	Application efficiency
Microirrigation	80-95%
Sprinkler	60-80%
Surface/Seepage	20-70%

Table 1. Application efficiency for water delivery system (Simonne & Dukes, 2009)

Microirrigation systems: Application efficiencies of microirrigation systems are typically high because these systems distribute water near or directly into the crop root zone, and water losses due to wind drift and evaporation are typically small (Boman & Parsons, 2002; Locascio, 2005). This highly efficient water system (90% to 95%; Table 1) is widely used on high value vegetables and tree fruit crops. The advantages of microirrigation over sprinkler include reduced water use, ability to apply fertilizer with the irrigation, precise water distribution, reduced foliar diseases, and the ability to electronically scheduled irrigation on large areas with relatively smaller pumps. If micro-sprinkler systems are operated under windy conditions on hot, dry days, wind drift and evaporation losses can be high. Thus, management to avoid these losses is important to achieving high application efficiencies with these systems. The most common application of microirrigation in Florida, USA is that of under-tree micro-sprinkler systems for citrus. Less efficiency has been found for micro-sprinkler system compared to drip irrigation system. Application efficiencies of drip and line source systems are primarily dependent on hydraulics of design of these systems and on their maintenance and management (Boman & Parsons, 2002).

Sprinkler system: Sprinkler systems are designed to use overlapping patterns to provide uniform coverage over an irrigated area. Sprinklers are normally spaced 50-60% of their diameter of coverage to provide uniform application in low wind conditions. Studies have shown that 1.5% to 7.6% of irrigated water can be lost due to wind drift and evaporation during application (Dukes et al., 2010). Application efficiencies of sprinkler systems are relatively low at less than 80% (Table 1). Because networks of pressurized pipelines are used to distribute water in these systems, the uniformity of water application and the irrigation efficiency is more strongly dependent on the hydraulic properties of the pipe network. Thus, application efficiencies of well-designed and well-managed pressurized sprinkler systems are much less variable than those of gravity flow irrigation systems, which depend heavily on soil hydraulic characteristics. Therefore, during water applications, sprinkler irrigation systems lose water due to evaporation and wind drift (Haman et al., 2005). More water is lost during windy conditions than calm conditions. More is also lost during high evaporative demand periods (hot and dry days) than during low demand periods (cool, cloudy, and humid days). Thus, sprinkler irrigation systems usually apply water more efficiently at night (and early mornings and late evenings) than during the day. It is not possible to apply water with perfect uniformity because of friction losses, elevation changes, manufacturing variation in components, and other factors. Traveling guns typically have greater application efficiencies than portable guns because of the greater uniformity that occurs in the direction of travel (Smajstrla et al., 2002). Periodic move lateral systems are designed to apply water uniformly along the laterals. No uniformity and low application efficiencies occur when the laterals are not properly positioned between settings. Non-uniformity also occurs at the ends of the laterals where sprinkler overlap is not adequate (Smajstrla et al., 2002).

Surface and Seepage systems: Water is distributed by flow through the soil profile or over the soil surface. The uniformity and efficiency of the irrigation water applied by the surface

irrigation system depends strongly on the soil topography and hydraulic properties (Boman & Parsons, 2002). Florida's humid climate requires drainage on high water table soils, and field slope is necessary for surface drainage. But surface runoff also occurs because of field slope. Runoff reduces irrigation application efficiencies unless this water is collected in detention ponds and used for irrigation at a later time (Smajstrla et al., 2002). Water distribution from seepage irrigation system occurs below the soil surface. Therefore, wind and other climatic factors do not affect the uniformity of water application. Use of a well-designed and well-maintained irrigation systems can reduce the loss of water and thereby increase application efficiency as well as uniformity (Boman & Parsons, 2002).

3.2 Development and characteristics of "gradient-mulch" system

In the 1960's, a vegetable production system on sandy soils was developed in south Florida using a "gradient-mulch" concept to supply nutrients to plants under seepage irrigation (Geraldson, 1962; Geraldson et al., 1965). This system dominates contemporary vegetable production on Florida's sandy soils. The gradient-mulch system involves soil fumigation and banded application of soluble fertilizers beneath full bed plastic mulch. The system has been proven to provide a controlled environment within the bedded soil for sufficient nutrient supply, optimum soil moisture content, stable root growth, and managements for weed, disease, and insect.

Basic components of the gradient-mulch system include 70- to 90 cm-wide (depending on vegetables) flat topped soil beds raised 25- to 30-cm above from ground, covered by full plastic mulch (Fig. 1). Soluble fertilizers such as N and potassium (K) are applied as band on or near (top 0 to 4 cm) the soil bed surface with the more insoluble nutrients such as phosphorus (P) and micronutrients mixed in the bed. Seepage irrigation is provided to maintain a constant water table levels that are typically 40 to 45 cm deep in Florida sandy soils. Intermittent ditches are also provided for irrigation and drainage purposes from a precisely leveled field with a slope of about 2.5 cm in 30 m (Fig. 2).

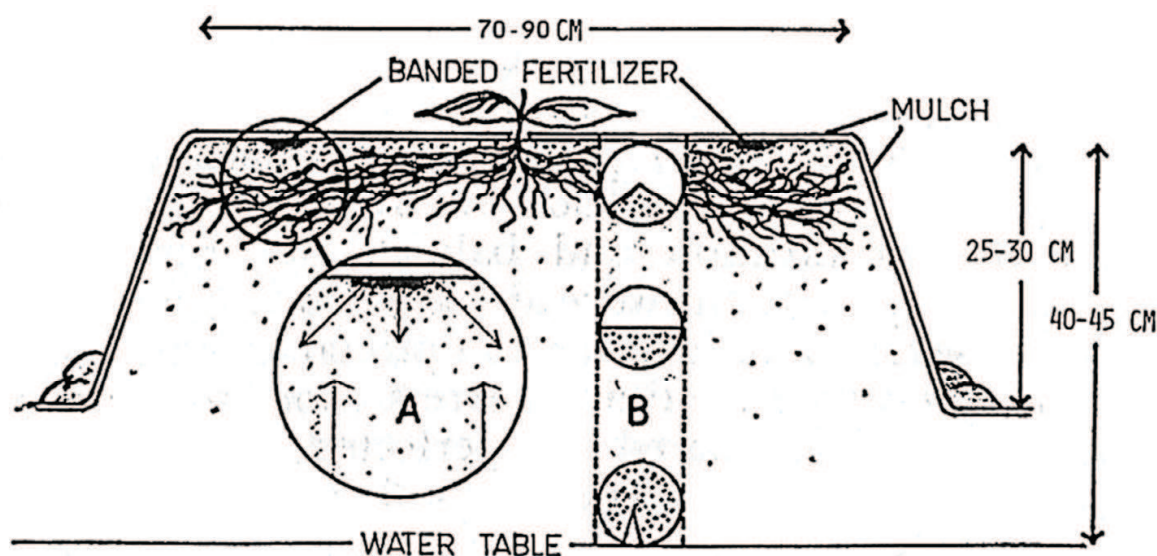


Fig. 1. Diagram of the gradient-mulch system. A. Three-dimensional nutrient gradient where salts diffuse outward from level of highest concentration, and move upward with moisture. B. Two-dimensional moisture-air gradient where moisture moves upward (modified from Geraldson, 1980)

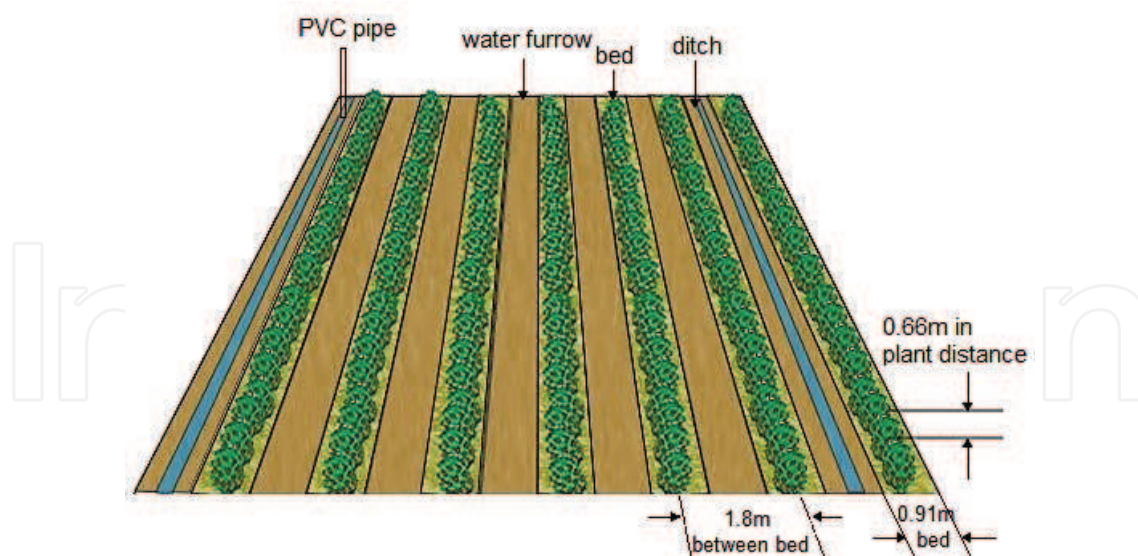


Fig. 2. Diagram of typical gradient-mulch system in a field. A ditch runs between every six raised beds of 91-cm width with 1.8-m distance between beds. For example, tomato plants are 66-cm apart from each other on the bed

Use of a full-bed synthetic mulches on soil beds can serve for minimum nutrient loss by leaching, minimum evaporation loss, optimum soil temperature and moisture/air ratio, and weed and ground rots control (Geraldson, 1981). A reciprocal moisture-air gradient is provided by maintaining the constant water table a given distance below the flat topped soil bed. Thus, a two-dimensional range of decreasing moisture/increasing air is established from a level of saturation to the bed surface. A three-dimensional concentration gradient decreasing with distance from the surface applied fertilizers is superimposed on the moisture-air gradient. Thus, the root from a germinating seed or transplanted seedling can develop in that portion of the bed where the most favorable levels of nutrients, moisture, and air coincide. Once the root system becomes established in a favorable portion of the soil bed, then nutrients and moisture must continue to be supplied to the root as removed by the root; soluble nutrients move by gradient diffusion from the surface to the root. The less soluble nutrients mixed in soil bed continue to become available by equilibrium action, also as removed by the root. Thus, a minimal stress root environment is established and maintained regardless of an increasing crop requirement.

Moisture is similarly supplied from the water table as required. It is important to recognize that a fluctuating water table can alter the stability of both the moisture and nutrient gradients. The depth of the water table can be a function of the design and management of both the drainage and irrigation system (Geraldson, 1981). Many sandy soils in Florida such as Spodosols favor the use of a constant water table which is basic to the functional efficiency of the gradient-mulch system.

The required quantities of fertilizers used under the mulch for intensive production are no problem if used as recommended. However, when finished and the mulch is removed, it would be preferable to have a minimal residue of salts, thus minimal leaching of salts out of the field (minimal pollution) and minimal salts that might accumulate (minimal stress). Residual salts, irrigation water salts, and misplaced fertilizer salts contribute to a salt buildup in the root environment. Accumulation beyond a given concentration progressively reduces production efficiency (Geraldson, 1981).

For tomato production, for example, under the gradient-mulch system with seepage irrigation, all P_2O_5 , micronutrients, and 20 to 25% of N and K_2O are broadcast and incorporated into the bed (i.e., “bottom” or “cold” mix). The remaining N and K_2O are placed in narrow grooves 5 to 8 cm deep and 30 to 35 cm offset from the plant bed center (i.e., “top” or “hot” mix). Supplemental N and K_2O at 13.6 and 9.1 kg, respectively, can be applied by liquid fertilizer injection wheel to replace leached N and K_2O (Olson et al., 2009). Therefore, nutrient concentrations can differ considerably with location in the bed and with time throughout the growing season. For example, soil solution NO_3^- -N concentrations at the fertilizer band and crop row of a tomato bed at the beginning of the growing season were 4200 and 263 mg L^{-1} at the 0–5 cm depth and 900 and 25 mg L^{-1} at the 10–20 cm depth, respectively. By the end of the growing season, NO_3^- -N concentrations at the band and row had significantly decreased to 250 and 129 mg L^{-1} at the shallow depth and 115 and 10 mg L^{-1} at the deeper depth, respectively (Geraldson, 1999).

The gradient-mulch system was an important factor in improving production efficiency in the Florida tomato industry during the 1970's. The productivity improved 2.5 times with the system compared with that without the system, and the value of the 1979-80 Florida tomato crop increased to \$228 million compared with \$92 million in 1972-73. This system started to be adopted for other crops such as pepper, sweet corn, cauliflower, eggplant, and squash (Geraldson, 1981). Today, as of 2009, the state of Florida has grown to be the second state following California in acreage for fresh tomato production (14,800 and 14,000 ha in California and Florida, respectively), and the leading state in fresh tomato production value in the USA exceeding \$520 million which accounted for 26% of the state's total crop production value (USDA/NASS, 2011).

4. Nutrient mobility and availability for vegetable production on sandy soils

4.1 Nutrient availability under drip irrigation systems

The use of plastic mulch and drip irrigation has become more common in high intensity vegetable production on sandy soils than sprinkler and seepage irrigation systems because water application efficiency, defined as the fraction of the water applied and that is available to plant for use, is greater with drip system than with sprinkler and seepage systems (Simonne & Dukes, 2009; Table 1). However, excess irrigation practices can cause reduced water application efficiency and leaching of soluble nutrients out of the root zone. Although irrigation and fertigation practices vary widely among growers, irrigation typically occurs once or twice each day with regularly scheduled time normally and prolonged time during peak growth stages, while fertigation only takes place 1 to 2 times each week.

Soluble nutrients such as NO_3^- -N are transported mainly by convection with water mobility, therefore can move through soil profile with water applied using drip irrigation system. It is evident that the reduction in water moving through the root zone corresponds to a reduction in the amount of NO_3^- -N lost below the root zone. When drip irrigation management was improved using more controlled irrigation scheduling than traditional fixed time scheduling, the amounts of water thus NO_3^- -N leached out of the root zone were reduced (Dukes et al., 2006). In experiments for tomato and green bell pepper grown on Candler and Tavares sands (both 97% sand), USA, N was applied at 192 and 208 kg ha^{-1} to tomato and bell pepper, respectively. Electric probes installed in soil beds measured soil water content in the beds and functioned as a bypass controller to skip a scheduled timed irrigation event if the soil volumetric water content (VWC) was above a preset threshold.

When a probe installed in the tomato bed was set the threshold for soil VWC of 13%, the amount of excess irrigation water leached out of the root zone (below 60 cm) was 84% less compared to that with the fixed time scheduling irrigation system (6.8 vs. 42.8 mm). Similarly, the amount of NO_3^- -N leached was reduced to 82% between the controlled and fixed time scheduling irrigation systems (7 vs. 37 kg NO_3^- -N ha^{-1}). On bell pepper using the threshold of 10% and 13% VWC, the controlled irrigation system reduced water leaching by 81% and 51%, respectively, as well as NO_3^- -N leaching by 84% and 20%, respectively, compared to the fixed irrigation system. While tomato showed an increase in crop yield, bell pepper exhibited a significant reduction in crop yield especially when the VWC was maintained to 10% (Dukes et al., 2006).

Otherwise, the less mobile nutrients such as P are transported mainly by diffusion, hence its mobility in soils is less strongly governed by water mobility than the mobile nutrients. Triple superphosphate (0-45-0) was applied as P fertilizer with four different rates (0, 30, 60, and 90 kg ha^{-1}) and two different water management regimes (drip irrigation and non-irrigation) to tomatoes grown on Granby loamy sands (77 to 82% sand), Canada for two consecutive years (2007-2008) (Liu et al., 2011). For both growing seasons, in the 0-40 cm soil profile, water extractable P (WEP) content was lower in the drip irrigation treatment than in the non-irrigation treatment (Fig. 3a). However, irrigation management did not have significant effects on WEP below 40-cm depth. Similarly, soil WEP content significantly increased with increasing fertilizer P rate applied only in the top 0-40 cm profile, but not below the depth of 40 cm (Fig. 3b). It appeared that the reduced WEP in the top 0-40 cm with the drip irrigation treatment may have caused by increased crop uptake of P with drip irrigation rather than the vertical mobility of P with water. The drip irrigation of P can provide precise amounts of water and nutrients in an efficient manner, optimizing plant uptake and minimizing environmental losses (Hartz & Hochmuth, 1996). However, environmental losses of P through vertical leaching can occur in sandy soils with high hydraulic conductivity, low P adsorption capacity, and shallow water table levels (Leinweber et al., 1999; Djodjic et al., 2004).

It appears that fertigation with 100% water-soluble fertilizers applied through drip irrigation (i.e., drip fertigation) can reduce the amount of leachable fertilizers such as NO_3^- -N and K to deeper soil layers, compared to soluble fertilizers applied to soil with water applied by drip irrigation. However, less mobile nutrients such as P tend to be fixed at the point of application. Yet, subsurface drip fertigation can cause higher available P in deeper layers. Tomatoes were grown on sandy loam soil in India with fertilizer rates of 180-66-99.6 kg N-P-K ha^{-1} using urea, single superphosphate, and muriate of potash as normal fertilizer for drip irrigation, and urea, mono-ammonium phosphate (12-26.84-0), and potassium nitrate (13-0-38.18) as 100% water-soluble fertilizer for fertigation, both applied daily through in-line drippers (Hebbar et al., 2004). After 2 years of growing seasons of 116 and 119 days, respectively, lower residual NO_3^- -N was observed at 30-45 cm soil layer in the fertigation treatment (55 kg ha^{-1}) than in the drip irrigation treatment (66 kg ha^{-1}). The reduction in the residual NO_3^- -N was further enhanced at 45-60 cm soil layer. Similarly, the residual exchangeable K (by 1 N ammonium acetate) accumulation was higher at deeper layers (30-45 and 45-60 cm) in drip irrigation treatment, compared with the fertigation treatment (93 vs. 83 kg ha^{-1} and 95 vs. 72 kg ha^{-1} , respectively). However, the level of available P (by Bray 1) was significantly higher in 15-30 cm (62 kg ha^{-1}), 30-45 cm (36 kg ha^{-1}), and 45-60 cm (22 kg ha^{-1}) depths in the subsurface drip irrigation compared to the drip irrigation treatment.

Because P fertilizer was delivered at 20 cm below the surface by means buried laterals, more concentration of P was observed at deeper depths (Hebbar et al., 2004).

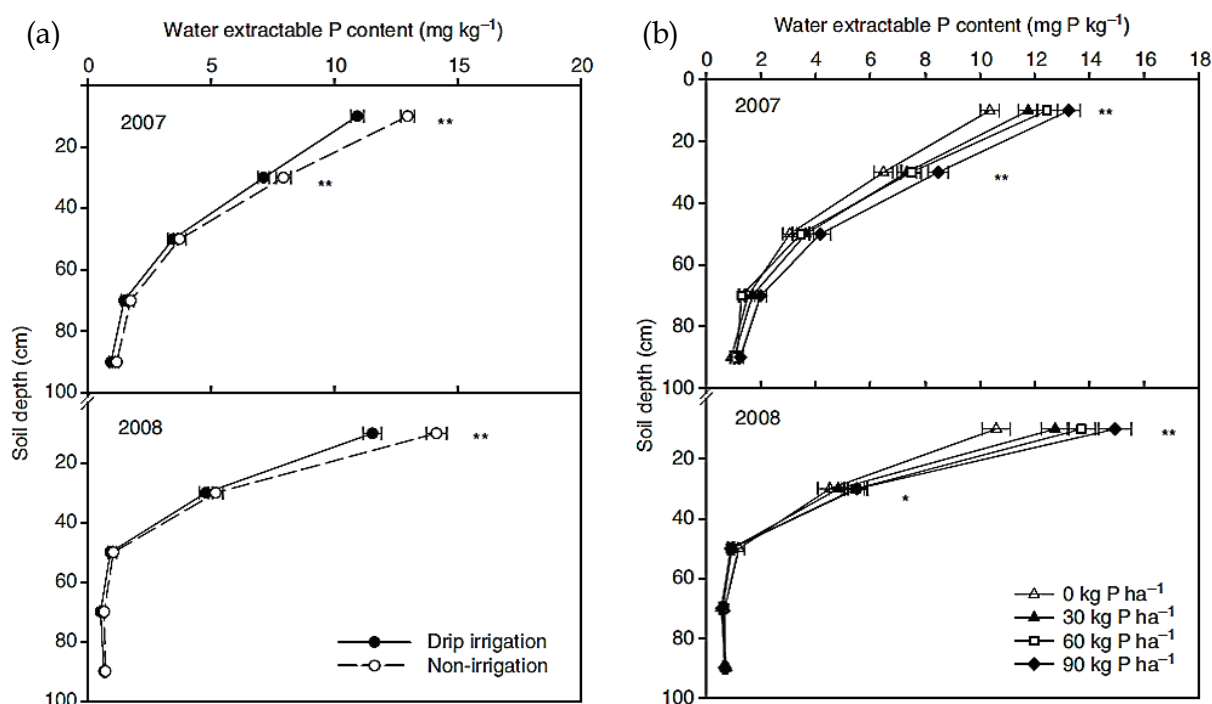


Fig. 3. Post-harvest water-extractable P in the 0- to 100-cm soil profile as affected by (a) different water management regimes and (b) fertilizer P application rates under processing tomato at Harrow, Ontario, 2007-2008 (adapted from Liu et al., 2011)

4.2 Nutrient mobility in soil under seepage irrigation

The spatial and temporal distribution of nutrients and transformation between chemical forms within the soil bed throughout the growing season under seepage-irrigated sandy soils have rarely documented. It is critical, however, to understand dynamics of nutrient mobility in the soil bed for proper fertilization and irrigation managements or best management practices for vegetable production. Tomatoes were grown on Holopaw fine sand (98% sand), USA using the gradient-mulch system with plastic mulch under seepage irrigation (Sato et al., 2009a, 2009b). Total fertilizer rates applied were 224–61–553 kg N–P–K ha⁻¹. While N and K were applied with the bottom (17 kg N ha⁻¹ and 27 kg K ha⁻¹) and top mix (207 kg N ha⁻¹ and 526 kg K ha⁻¹), all P was applied only with the bottom mix. Soil samples were collected using an auger weekly or biweekly for 18 wk after planting (WAP) at two locations (the fertilizer band and the bed centerline) at three different depths with 10-cm increment (Fig. 4). Each sampling location was denoted as B1: band and top, B2: band and middle, B3: band and bottom, C1: centerline and top, C2: centerline and middle, and C3: centerline and bottom. The soil samples were analyzed for ammonium-N (NH₄⁺-N) and NO₃⁻-N by 2 M KCl, and available P and K by Mehlich-1 extractions.

The NH₄⁺-N concentration at B1 location was highest throughout the season compared with other locations, and in general steadily decreased with time (Fig. 5a). Initially low NH₄⁺-N at C1 location peaked during 3 to 5 WAP, and elevated NH₄⁺-N concentrations were found at C2 location as well until 5 WAP. Most NH₄⁺-N resided at B1, B2, C1, and C2 locations

because N was applied in the top mix placed directly above B1 and B2, and also in the bottom mix that was incorporated into the soil (C1 and C2) when the raised bed was formed. However, the N rate applied as the bottom mix (17 kg N ha⁻¹, equivalent to 8.5 mg N kg⁻¹ when broadcast in the top 15 cm of soil) was too small to account for the NH₄⁺-N concentrations found at C1 and C2 locations (ranging from 50 and 100 mg N kg⁻¹ until 5 WAP), indicating translocation (lateral mobility) of NH₄⁺-N most likely from B1 location. The NH₄⁺-N concentrations below 20-cm depth were consistently low or non-existent throughout the season, indicating that NH₄⁺-N virtually did not move vertically below 20-cm depth under seepage irrigation (Sato et al., 2009a).

The NO₃⁻-N concentration at B1 location peaked during 3 WAP, which was 2 to 3 wk later than the NH₄⁺-N peak, then slowly decreased with time (Fig. 5b). This may indicate that it took about 3 wk for NH₄⁺-N at B1 to process nitrification that commenced about 2 wk into the season. The most notable behavior of NO₃⁻-N was an elevated concentration peak during 6 to 8 WAP at every location in the bed except for B1 (which remained much higher than the rest of the locations throughout the season), and subsequent decrease to almost zero at the end of the season. This peak corresponded with a raised water table level and accordingly increased soil water content, especially in the middle and bottom layers during 5 to 7 WAP. Since water is supplied to the root zone by capillarity under seepage irrigation, it is critical to maintain the water table at a depth that supplies sufficient upward flux. The water table depth below the bed surface was relatively stable at recommended levels between 45 and 60 cm for seepage-irrigated tomato bed (Stanley and Clark, 2003) except for two elevations that occurred during 2 WAP (43 cm) and 5 WAP (26 cm). On the other hand, the water table fluctuation did not appear to influence NH₄⁺-N in any part of the bed since the NH₄⁺-N steadily decreased after 5 WAP at every location in the bed. This difference could be due mainly to different diffusivity of the two ions, given the same soil properties

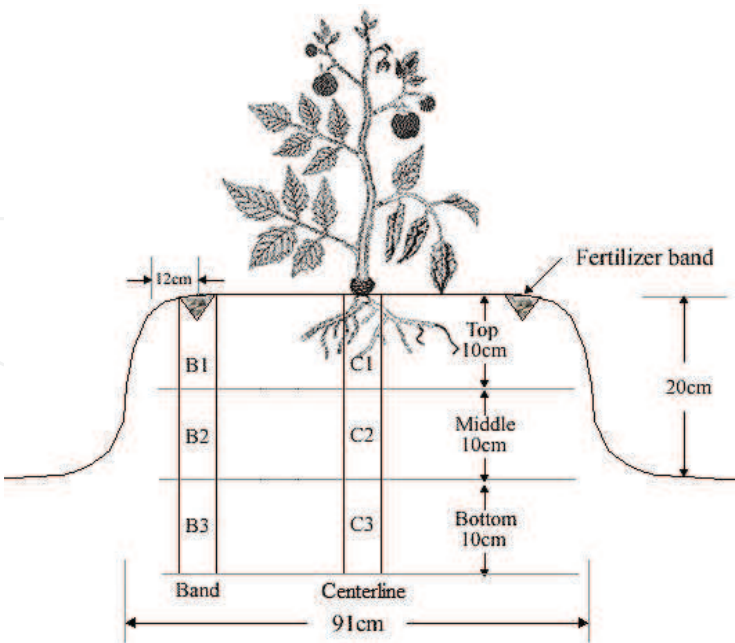


Fig. 4. Cross-sectional diagram of tomato bed and sampling locations in the bed. B1: band and top, B2: band and middle, B3: band and bottom, C1: centerline and top, C2: centerline and middle, and C3: centerline and bottom (modified from Sato et al., 2009a)

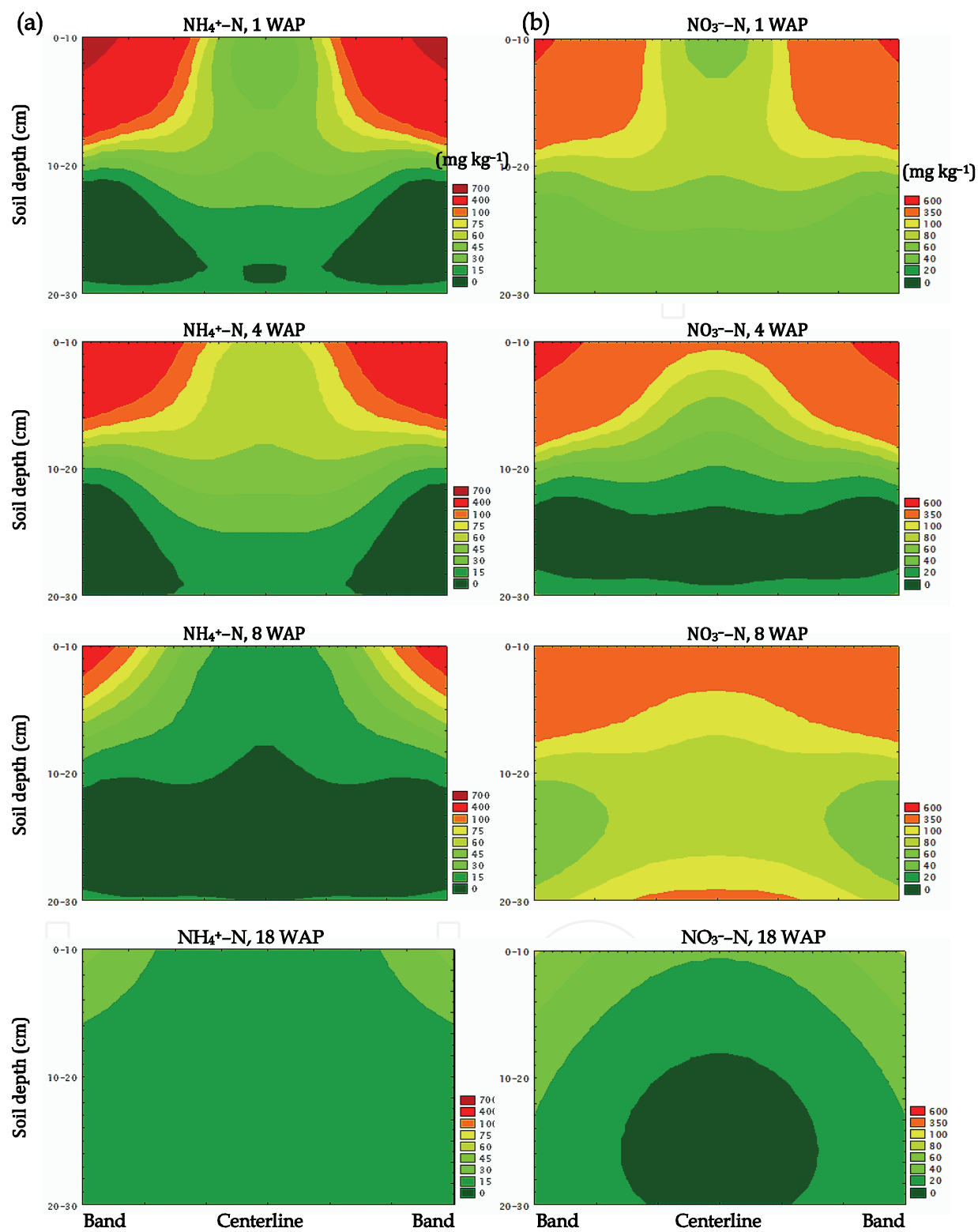


Fig. 5. Cross-sectional diagrams of spatial distribution of (a) $\text{NH}_4^+\text{-N}$ and (b) $\text{NO}_3^-\text{-N}$ in soil bed during 1, 4, 8, and 18 wk after planting (WAP). The concentrations in the soil bed are assumed to be symmetrical about the centerline on both sides of fertilizer band

affecting the ion mobility in soil such as soil hydraulic conductivity, water-holding capacity, texture, porosity, and density. Increased diffusivity of NO_3^- -N with increased water content in the middle and bottom layers during 5 to 7 WAP would have greatly facilitated both lateral and vertical mobility of NO_3^- -N (Sato et al., 2009a). The key to the stability of moisture and nutrient gradients and the root environment in the gradient-mulch system under seepage irrigation is the constant water table that is often difficult to maintain due to periodic rains and complex management of drainage and irrigation (Geraldson, 1980, 1981).

Most of P remained at C1 and C2 locations in the bed ranging between 150 and 400 mg kg⁻¹ with gradual decrease at the end of the season, while P in the rest of the bed did not change to a great extent maintaining less than 100 mg kg⁻¹ throughout the season. Since it is a common practice under the seepage irrigation system to apply P fertilizer only in the bottom mix to target the root zone, the bottom mix was broadcast on the surface soil before bedding, and the soil was then pushed by discs at the outer edges of the bedding apparatus toward center to form the raised bed. Therefore, most of P was initially placed in C1 and C2 and remained in the root zone. This implies that P did not move outside the root zone regardless of water table fluctuations and soil water content (Sato et al., 2009b).

Most of K in the bed remained in B1 location at an order of magnitude higher concentration (from 4000 up to 12000 mg kg⁻¹) than other bed locations because most of K fertilizer was applied in the top mix. The K concentrations in C1 and C2 locations maintained relatively high concentrations (100 to 180 mg kg⁻¹) until 7 to 8 WAP, then decreased to low values, possibly because of the bottom mix of some of K fertilizer. The K concentrations in the bottom layer were consistently low and did not greatly change throughout the season, except a raised concentration during 7 WAP. Although the substantial amounts of K were present in B1 location at the end of the season, remarkably low K concentrations were found in the rest of the bed after production. This indicates that under gradient-mulch system minimum K leaching occurred during the growing season, except for possible K loss through leaching to some extent during 5 to 7 WAP when water table fluctuation was observed, as similarly seen with NO_3^- -N (Sato et al., 2009b).

4.3 Nutrient availability from controlled- and slow-release fertilizers

The use of controlled-release fertilizers (CRFs) and slow-release fertilizers (SRFs) for vegetable productions on sandy soils has been investigated with varying results, and nutrient availability on sandy soils from CRFs and SRFs has been increasingly clarified (Simonne and Hutchinson, 2005). Nitrogen (NH_4^+ -N + NO_3^- -N) availability from the total of 18 different CRFs (plus 4 different soluble fertilizers as comparison) mixed in Ellzey fine sand (94% sand), USA was evaluated in a plastic pot through which 400 mL of water was leached every 7 d for 12 times. The N rates applied were 6.18 and 4.80 g pot⁻¹ for 2001 and 2002 trials, respectively (the 2001 rate corresponded to 224 kg N ha⁻¹). While the soluble fertilizers leached 82–98% of applied N after 12 leaching events, leached N from CRFs ranged between 13–38% in 2001 and 22–49% in 2002. Some CRFs may not release 100% of the coated N as the thickness of some prills may permanently prevent N release. The fraction of N never released is termed “locked-up N” (Simonne & Hutchinson, 2005). Nevertheless, all CRFs tested did not release N rapidly enough to supply adequate N to vegetable crops. However, since all CRFs tested except for 2 types had urea as the only N source, most of the N recovered was in the NH_4^+ -N form. The NH_4^+ -N release pattern from

some CRFs was similar to those of the soluble fertilizers and closely desirable for vegetable production.

Many researches have demonstrated that CRFs and SRFs can reduce N, particularly NO₃⁻-N leaching on sandy soils compared with soluble fertilizers (Alva, 1992; Wang & Alva, 1996; Paramasivam & Alva, 1997; Fan & Li, 2009). Moreover, not only NO₃⁻-N but also other nutrients such as P, K, calcium (Ca), magnesium (Mg), and copper (Cu) can CRFs reduce leaching compared with uncoated fertilizers. Four different coated CRFs were compared with an uncoated (soluble) fertilizer on a sandy clay loam of Bungor soil (Typic Paleudult), Malaysia for nutrient leaching in soil columns for 30 d (Hanafi et al., 2002). The percentages of the amount of nutrients leached on the nutrients initially applied ranged 23–33%, 2–4%, 10–19%, 2–9%, 4–9%, and 1–3%, whereas those of the uncoated fertilizer were 80%, 28%, 90%, 29%, 20%, and 6% for N, P, K, Ca, Mg, and Cu, respectively. On the other hand, the distribution of the amount of N, P, and K left in the soil profile after 30 d of leaching differed depending on the type of fertilizers (Table 2). Nitrogen and K left in the soil from the uncoated fertilizer were almost evenly distributed among 0–6, 6–12, and 12–18 cm depths, with almost all P was accumulated only in the top 0–6 cm depth. Almost a half of N and K left in the soil from the coated fertilizers was found only in the top 0–6 cm depth, while up to 90% of P left in the soil was in the top depth with up to 15% found in the 6–12 cm depth. Accumulation of nutrients released from CRFs in upper soil layers appears to enhance the reduction of nutrient leaching from CRFs compared with those from soluble fertilizers.

Soil depth	Uncoated fertilizer			Coated fertilizers		
	N	P	K	N	P	K
cm	%			%		
0–6	35	97	26	47–49	84–90	43–51
6–12	29	2	24	13–15	8–15	19–29
12–18	29	1	21	13–14	1–2	16–19
18–24	4	0	16	13–16	0–1	5–14
24–30	3	0	13	9–12	0	1–8
	mg kg ⁻¹			mg kg ⁻¹		
0–30	732	172	497	2341–2694	235–267	3410–4043

Table 2. The percentage of the amount of nutrients left at different soil depths after leaching for 30 d on the total amount of nutrients left in the soil profile (0–30 cm). Coated fertilizers show ranges of the percentage of 4 different CRFs tested (made from Hanafi et al., 2002)

Nutrient use efficiency, particularly for N using CRFs or SRFs may be improved compared to that using soluble fertilizers (Shaviv & Mikkelsen, 1993). The NUE for N ranged between 10% and 32% for uncoated fertilizer and between 79% and 94% for coated fertilizers when peanut was grown on a sandy soil (Typic Udipsamment), Japan under drip irrigation with N application rates of 30 to 120 kg ha⁻¹ (Wen et al., 2001). Seepage-irrigated Irish potato produced on Elley fine sand (90–95% sand), USA had a significantly higher NUE for N with CRFs treatment compared with soluble fertilizer treatment only when 112 kg N ha⁻¹ was

applied, but not when 168 and 224 kg N ha⁻¹ were applied (Hutchinson et al., 2003). Other studies showed similar results of higher NUE for N with CRFs compared with soluble fertilizers only with lower N application rate applied, but not with higher rate (140 vs. 280 kg N ha⁻¹; Zvomuya et al., 2003; and 146 vs. 225 kg N ha⁻¹; Pack et al., 2006; both for potato production on sandy soils). Nutrient availability caused by the use of CRFs and SRFs over the soluble fertilizer can be improved by the interaction and competition between plant roots, soil microorganisms, chemical reactions, and pathways for loss, and matching nutrient release with plant demand (Shaviv & Mikkelsen, 1993).

4.4 Availability of nutrients applied with organic waste materials

Nutrient availability from organic waste materials such as composts and biosolids when applied in sandy soils is different from, and more difficult to be clarified as organic materials involve more factors and processes in determining nutrient availability than chemical fertilizers (Mylavarapu & Zinati, 2009). Particularly, N is more complicated than other nutrients because the transformation of compost N varies widely among different sources and is affected by soil properties, compost characteristics, and environmental factors (Sims, 1995; Amlinger et al., 2003). The mineralization of one biosolid and two composts with C/N ratio ranging between 5.8 and 38.0 and organic N between 2.9 and 49.0 g kg⁻¹ was evaluated for one-year period in field-conditioned columns packed with Oldsmar sand, USA (He et al., 2000). Both rate and the total amount of mineralized N (NH₄⁺-N + NO₃⁻-N) from the biosolid (lower C/N ratio and higher organic N content) were greater than those from the composts (higher C/N ratio and lower organic N content) during the incubation. While the biosolid reached a peak of the mineralized N within the first 90 d of the incubation, the composts had two distinct peaks at about 90 d and about 280 d of the incubation. The first and second peaks of N mineralization from these materials might be the results of its relatively uniform components made of sewage sludge in both materials and grass clippings and wood chips mixed only in the composts, respectively (He et al., 2000). The mobility of the mineralized N in soil column also differed among these materials. While only small portion of the mineralized NH₄⁺-N (9% of the total NH₄⁺-N for the biosolid) leached out of the column of 20-cm depth, 56% of the mineralized NO₃⁻-N in the total NO₃⁻-N for the biosolid leached out almost constantly throughout the incubation. On the other hand, the composts had leaching of the mineralized NH₄⁺-N (57–65% of the total NH₄⁺-N for the composts) constantly throughout the incubation, on average 75–85% of the mineralized NO₃⁻-N of the total NO₃⁻-N for the composts leached out during the second half of the incubation. Application and management of the organic materials when utilized as N fertilization need to be carefully considered to minimize the risk of NO₃⁻-N leaching on sandy soils, especially when the materials contain high amounts of materials with low C/N ratio such as sewage sludge-derived biosolids.

The biosolids produced by different treatment processes contain varying amounts of mineral and organic N and the organic components may be stabilized to varying degrees. Unstabilized biosolids usually contains high available C, thus high C/N ratio, and may cause a net reduction of mineralized N in amended soils due to immobilization during incubation (Epstein et al., 1978; Parker & Sommers, 1983). The N immobilization in the amended soil may occur when the C/N ratio of the biosolids exceeds 15 (Epstein et al., 1978) or 20 (Parker & Sommers, 1983). Twelve different biosolids produced at 8 different sewage treatment facilities in the UK were incubated for 73 d in a loamy sand soil (86% sand) (Smith

et al., 1998). All biosolids showed a concomitant reduction in $\text{NH}_4^+\text{-N}$ concentration with the formation of $\text{NO}_3^-\text{-N}$ in the amended soil with increasing time of incubation. Indeed, all except dewatered undigested biosolids exhibited an initial rapid $\text{NO}_3^-\text{-N}$ accumulation followed by a slower release reaching maximum amounts of $\text{NO}_3^-\text{-N}$ production. In contrast, the dewatered undigested biosolids, which contained higher amounts of OM among the biosolids tested, showed a significant immobilization of mineral N in the amended soil during the initial stages of incubation. Based on the N mineralization patterns in incubated soil, 4 categories of the biosolids were proposed (Smith et al., 1998). They are: category 1 – liquid digested and lagooned liquid undigested biosolids that have the greatest $\text{NO}_3^-\text{-N}$ accumulation potential due to large content of $\text{NH}_4^+\text{-N}$; category 2 – liquid undigested, lagooned liquid digested, and dewatered digested biosolids have low to intermediate $\text{NO}_3^-\text{-N}$ accumulation potential; category 3 – dewatered undigested biosolids are high in available C and may produce an initial net N immobilization followed by $\text{NO}_3^-\text{-N}$ accumulation after soil microbes has metabolized the added substrate C; and category 4 – air-dried digested biosolids are relatively resistant to mineralization and $\text{NO}_3^-\text{-N}$ formation in soil. The C/N ratio of the biosolids of category 1 to 4 is generally ordered from the lowest to the highest.

When the biosolids and manure are applied to soil based on crop N requirements, P in excess of crop needs is usually supplied due to high P content in the organic wastes. Environmental loss of P by surface runoff or leaching from organic wastes application can be significant in areas with shallow groundwater and coarse-textured soils of low P-holding capacities (Eghball et al., 1996; Lu & O'Connor, 2001). Leachability of eight different biosolids was compared with that of a chemical fertilizer (triple superphosphate, TSP) in a column study for 4 months on Candler and Immokalee sandy soils, USA with the application rates of 56 and 224 kg ha⁻¹, corresponding to typical application rates based on P-based and N-based fertility, respectively (Elliott et al., 2002). Candler and Immokalee soils had moderate and very low P-sorbing capacities, respectively, as indicated by the sum of oxalate-extractable Fe and Al. On Candler sand, the percentage of applied P leached ranged between 1.7% and 21.7% in the TSP treatment, and 0.05% and 0.45% in the biosolids treatment among two application rates. The percentage on Immokalee sand increased ranging between 13.6% and 20.7% from TSP, and 0.05% and 11.1% from the biosolids regardless of the application rates. It appears that the leachability of P from the biosolids is lower than that from the chemical fertilizer and considered as minor or negligible in many soils (Peterson et al., 1994; Sui et al., 1999).

However, the P leachability of the biosolids depends on the P-sorbing capacity of the soil; soils with lower sorbing capacity are more susceptible to P leaching. The extent of the biosolids-P leachability also appears to be explained by the P saturation index (PSI) of the biosolids, calculated as the ratio of oxalate-extractable P to the sum of oxalate-extractable Fe and Al (Jaber et al., 2006). The PSI is a measure of the degree to which biosolids P is potentially bound with Fe and Al. Therefore, PSI values < 1 suggest excess Fe and Al for binding P, and values > 1 suggest available P beyond that associated with Fe and Al precipitates. For the biosolids tested in Elliott et al. (2002), no appreciable P leaching occurred from soils amended with biosolids of PSI < 1.1, and Immokalee soil amended with biosolids of PSI > 1.3 exhibited substantial P leaching. The microbiological processes in the soil also play an important role in reducing P leaching from the biosolids in sandy soils (Yang et al., 2008). Application of the biosolids can result in the mineralization of OM from

the biosolids releasing OM-bound P as surplus to leachable P from the biosolids. However, the surplus P can be adsorbed on surfaces of Fe and Al oxides/hydroxides or immobilized to microbial biomass by increased microorganisms due to freshly added organic C from the biosolids, eventually reducing P leaching. More water-soluble P was incorporated into microbial biomass and organic fractions as evidenced by the increased microbial biomass P and microbial biomass carbon in the biosolids-amended soils (Yang et al., 2008). Nevertheless, mineralization of OM in sandy soils is generally fast particularly in humid climate conditions (Kang et al., 2011), therefore organic P including microbial biomass P can be considered to be available or potentially available to crop uptake.

5. Conclusion

Sandy-textured soils generally have low water- and nutrient-holding capacities, which, coupled with different irrigation systems used on sandy soils, make nutrient and irrigation managements difficult for suitable vegetable crop production. The nutrient and irrigation managements can be different and may be further complicated when impermeable layers such as argillic and spodic layers are excavated and mixed in as a result of the bedding process. Sandy soils, however, can be utilized for maximized crop production if proper managements for nutrients, irrigation, and drainage systems are implemented. The “gradient-mulch” system under seepage irrigation developed in 1960’s in Florida, USA has become the dominant system to provide a controlled environment within the bedded soil for sufficient nutrient supply, optimum soil moisture content, stable root growth, and managements for weed, disease, and insect. More importantly, nowadays, the gradient-mulch system has been proven to minimize environmental losses of nutrients, particularly NO_3^- -N and P below the root zone. Maintaining constant water table levels under seepage irrigation is, however, the most crucial factor for the gradient-mulch system for providing the maximized crop yields and minimized environmental losses of nutrients. In the light of the environmental concerns, CRFs and SFRs have been spotlighted for improved NUE, particularly for N for crop production under sandy soils. However, the effect of application of CRFs on vegetable crop production still need to be clearly understood in order for growers to receive full benefits from the use of these materials. Nutrient availability from organic waste materials such as composts and biosolids when applied in sandy soils is complex as the organic materials involve many factors and processes in determining nutrient availability. Particularly, the understanding on mineralization patterns of the organic materials with different properties under different soil and water managements is critical in determining the nutrient availability in soil and environmental fate of nutrients. Sandy soils can provide proper environmental conditions for appropriate vegetable crop production with suitable nutrient and irrigation management systems, therefore more studies are needed to elucidate the effect of different aspects of the production system in order for the producers to continue vegetable production without environmental damages, particularly from NO_3^- -N which can be the most prone nutrient for leaching in sandy soils.

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Soils play multiple roles in the quality of life throughout the world, not only as the resource for food production, but also as the support for our structures, the environment, the medium for waste disposal, water, and the storage of nutrients. A healthy soil can sustain biological productivity, maintain environmental quality, and promote plant and animal health. Understanding the impact of land management practices on soil properties and processes can provide useful indicators of economic and environmental sustainability. The sixteen chapters of this book orchestrate a multidisciplinary composition of current trends in soil health. Soil Health and Land Use Management provides a broad vision of the fundamental importance of soil health. In addition, the development of feasible management and remediation strategies to preserve and ameliorate the fitness of soils are discussed in this book. Strategies to improve land management and relevant case studies are covered, as well as the importance of characterizing soil properties to develop management and remediation strategies. Moreover, the current management of several environmental scenarios of high concern is presented, while the final chapters propose new methodologies for soil pollution assessment.

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